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CFD Modelling of Local Hemodynamics in Intracranial Aneurysms Harboring Arterial Branches

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Abstract. The main cause of non-traumatic subarachnoid haemorrhage is an intracranial aneurysm's rupture. The choice of treatment approach is exceptionally difficult in cases of aneurysms with additional branches on the aneurysm's dome or neck. The impact of the arterial branches on local hemodynamics is still unclear and controversial question. At the same time, up-to-date methods of image processing and mathematical modeling provide a way to investigate the hemodynamic environment of aneurysms. The paper discusses hemodynamic aspects of aneurysms harboring arterial branch through the use of patient-specific 3D models and computational fluid dynamics (CFD) methods. The analysis showed that the presence of the arterial branches has a great influence on flow streamlines and wall shear stress, particularly for side wall aneurysm.

Keywords. CFD modeling, intracranial aneurysm, hemodynamics.

Introduction

According to different authors the prevalence rate of unruptured cerebral aneurysm is about 3 to 5% [1]. Aneurysm rupture results in non-traumatic subarachnoid haemorrhage that carries high rates of mortality and disability [2]. Making a decision of surgical management is a particularly major challenge for patient with so-called complex aneurysm (CA). Up to the present day no formal definition exists on what CA are, but branches arising from the aneurysm itself are one of the commonly recognized features of CA [3,4]. There are only a few research works dedicated to investigation of this kind of CA. It is still unclear, if the arterial branch presents difficulties only for surgical access or it has a significant influence over local hemodynamics too. However the computational fluid dynamics (CFD) methods offer a wide range of possibilities to simulate hemodynamic changes in aneurysm [5]. To this end the purpose of this study was to assess the hemodynamics of CA with arterial branches by means of CFD simulations.

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1. Methods

1.1. Patients Data and Image Acquisition

CT angiography images of three patients with saccular cerebral aneurysm harboring a branch were utilized to generate three-dimensional models. The aneurysms were located on different vessels of the circle of Willis, their morphological characteristics are listed in table 1.

Table 1. Initial morphometric data of aneurysms

Morphological characteristics	Patient 1 Woman, 87 years	Patient 2 Man, 60 years	Patient 3 Woman, 55 years
Parent vessel	Internal carotid artery (ICA)	Anterior communicating artery (ACA)	Middle cerebral artery (MCA)
Dome height, mm	9	20	8
Dome width, mm	6	12	9
Neck width, mm	4.6	7	5
Aspect ratio	1.95	2.86	1.6

1.2. Computational Modeling

The anatomy of aneurysms was segmented and reconstructed with the software suite "Gamma Multivox D2" (Gammamed-Soft, Ltd, Russia). Three-dimensional geometric models were smoothed, and parametric conversion was performed. Virtual "removal" of branches was made for each model for further comparison study. In addition, models of patients 2 and 3 were resized to assess the influence of large size on hemodynamics. A total of 10 realistic models of aneurysm were used in this study (figure 1).

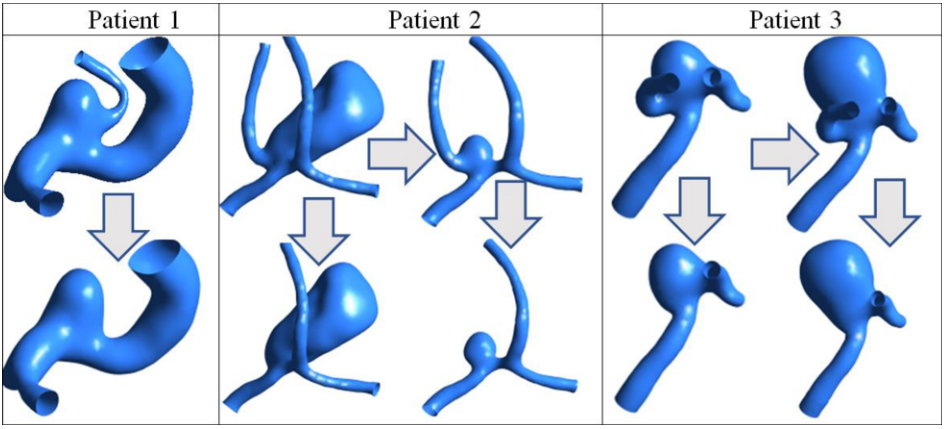

Figure 1. 3D models of aneurysms. The bottom row contains models after branch removal.

The following CFD simulations were carried out by means of ANSYS CFX v17.2 (ANSYS Inc., USA). Vessel walls were assumed to be rigid. Blood was modeled as an incompressible and Newtonian fluid with constant density 1060 kg/m3 and viscosity 0.0039 Pa*s. The inlet pulsatile flows were defined from doppler ultrasonography of healthy human. The peak systolic velocity for ICA, ACA and ACM were 100, 85 and 60 cm/s respectively. Beyond that we computed all 10 models with raised velocity (Vps=150 cm/s) to assess hemodynamic changes in conditions of pathological states.

The results are presented in terms of velocity profile, pressure and wall shear stress (WSS) distribution. Moreover, a new visualization technique was proposed that may improve interpretation of WSS distribution.

2. Results

CFD modelling showed mixed results. Analysis of the flow streamlines after branch removal showed lack of considerable changes in direction and force of stream for Patient 1. Conversely, for models of Patient 2 virtual removing of branch caused significant reduction of blood flow intensity in aneurysm sac (figure 2). As a consequence of this, WSS reduction was indicated. This effect was found for the small aneurysm as well as for the giant one. One of possible explanations of the discrepancy between two wall-side aneurysms could be the difference in the ratio of branches diameter to neck diameter. The ratio between sectional area of branch and sectional area of neck was equaled to 6.5 for Patient 1; only a small part of stream was directed to the branch. For Patient 2 this ratio was half as much.

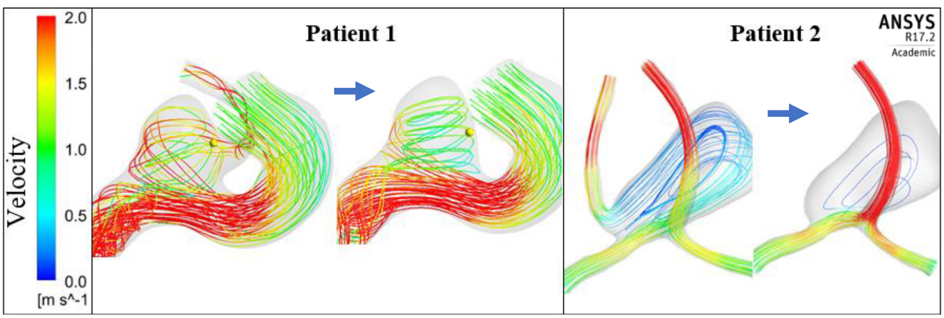

Figure 2. Comparison of velocity streamlines for patient 1 and 2 with and without arterial branch.

The branch removal on models for Patient 3 had not influence on local hemodynamics. We suppose that the bifurcation position of the aneurysm could be the cause: the dome of aneurysm was under the jet impact whether the arterial branch was present or not.

It is interesting to note that WSS growth rate was much higher for simulations with raised velocity (Figure 3). It means that in situations of angiospasm or hypertensive crisis not only values of WSS increase, but also the WSS variance in the area of jet. In other words, the values of WSS increased 3 times on the small area in comparison with other parts of aneurysm. The revealed trend can explain the fact that aneurysm rupture occurs at a time of elevation in blood pressure [6].

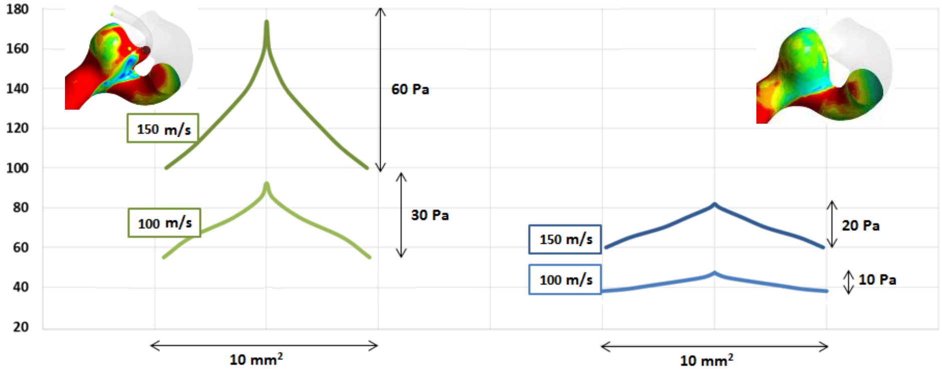

Figure 3. Comparison of WSS gradient near the area of jet for models with and without branch.

3. Discussion

In the light of this analysis we can suppose that presence of arterial branches on the dome or neck of aneurysm has a considerable impact on local hemodynamics. The nature of this impact depends on morphological characteristics and mostly on the relative position of aneurysm towards the parent vessel (side wall or bifurcation location). The bifurcation aneurysm was quite insensitive to branch removal: we found no significant changes of hemodynamics parameters. The variation of velocity profile and WSS of side wall aneurysm was much greater, the explanation of this requires the consideration of local and system factors [7]. It should be noted that a number of simplifying assumptions was made: we assumed rigid walls and Newtonian fluid. Also this study has a significant limitation due to the small number of patients. Overcoming this limitations and further studies would help surgeons to understand the hemodynamic changes induced by surgical treatment and to predict intra- and postoperative complications.

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